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MELBOURNE, VICTORIA

Aircraft Structures Technical Memorandum 478

THREE DIMENSIONAL COMPUTATION OF STRESS, STRAIN  
AND STRAIN ENERGY DENSITY UNDER INTERFERENCE-FIT  
AND AFTER COLD-WORKING OF HOLES. (U)

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by

R.P. CAREY

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THREE DIMENSIONAL COMPUTATION OF STRESS, STRAIN  
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R.P. CAREY

**SUMMARY**

Stress, strain and strain energy density distributions are computed by three-dimensional finite element analysis for interference fit and cold-worked conditions for a steel pin in an annular aluminium alloy plate, the plate thickness being equal to the pin diameter. Comparisons are made with the appropriate results from two-dimensional analyses.



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## 1. INTRODUCTION

In view of the wide usage of cold-working and interference-fits to improve the fatigue performance of bolted joints, a programme is proceeding at these laboratories to determine the stress/strain fields which are fundamental to the fatigue life enhancement process.

Previous studies (1,2) have examined the stress/strain fields using two-dimensional finite-element analyses and also an analytical treatment, with particular attention given to modelling interference by relative displacement loading (rather than uniform pressure loading which would be correct only for simple plate geometries). This paper extends the study to a three-dimensional finite element analysis whilst retaining relative displacement loading.

## 2. ANALYTICAL PROGRAM

The FEM computations were based on interference of a high-strength steel pin in a circular aluminium plate ten times the diameter of the pin. The plate thickness was taken equal to hole diameter. The assumed material properties are as given in Table 1 and the plate material has been considered to have bilinear stress/strain characteristics, Fig. 1, with isotropic strain-hardening. Because of the relatively high yield point for the pin material no allowance was required for yielding. Interference levels of 2% and 4% were simulated followed by unloading to a cold-worked state from both levels.

The FEM mesh for the plate was a 10 degree sector, as shown in Fig. 2(a), containing 56 twenty-noded, three-dimensional brick elements, and 18 fifteen-noded wedge elements. The pin mesh, shown in Fig. 2(b), contained 48 twenty-noded, three-dimensional brick elements and 64 fifteen-noded wedge elements. A small hole (2% of the pin radius) was created in the centre of the pin mesh to avoid a restriction on angular conformation.

The first phase of loading, inducing interference, involved forcing a uniform relative radial displacement between pin and plate nodes at the interface as previously described in Ref. 1. However representation of the cold-worked state was most conveniently carried out by switching to pressure loading and subsequent unloading, using the pressure distribution in the bore that was found with displacement loading. Removal of the simulated interface pressure was equivalent to removing the interference.

The analysis used the PAFEC finite element scheme (Level 6) on the ARL ELXSI computer. The plasticity routines of that scheme are based on Prandtl-Reuss equations in association with the von Mises' yield criterion.

## 3. RESULTS

Stress, strain and strain energy density relationships are presented graphically along with two-dimensional results from Ref. 2 which are included for comparison. The presentation of three-dimensional results is as follows :

- Fig. 3. Circumferential and radial stresses - interference.
- Fig. 5. Circumferential and radial stresses - unloaded.
- Fig. 7. Through-thickness stresses - interference.

- Fig. 9. Through-thickness stresses - unloaded.
- Fig. 10. Stress distribution in bore - interference.
- Fig. 11. Stress distribution in bore - unloaded.
- Fig. 12. Circumferential and radial strains - interference.
- Fig. 14. Circumferential and radial strains - unloaded.
- Fig. 16. Through-thickness strains - interference.
- Fig. 18. Through-thickness strains - unloaded.
- Fig. 19. Strain distribution in bore - interference.
- Fig. 20. Strain distribution in bore - unloaded.
- Fig. 21. Strain energy at the plate surface.
- Fig. 22. Strain energy at 0.563 of plate thickness from surface.
- Fig. 23. Strain energy distribution in bore.

Figs. 3,5,7,9,12,14,16 and 18 above show the variation of stress and strain, in the radial direction at three planes through the thickness, namely, at the surface, the mid-plane, and half-way between. The positions of mesh nodes, including mid-side nodes, are shown on Fig. 3(a) to give an indication of element size. Comparable distributions from the two-dimensional analysis where there is, of course, no variation in the thickness direction, are given as follows :

- Fig. 4. Circumferential and radial stresses - interference.
- Fig. 6. Circumferential and radial stresses - unloaded.
- Fig. 8. Through-thickness stresses - interference and unloaded.
- Fig. 13. Circumferential and radial strains - interference.
- Fig. 15. Circumferential and radial strains - unloaded.
- Fig. 17. Through-thickness strains - interference and unloaded.

It should be observed that, in the two-dimensional analyses, the mesh size in the radial direction was half that used in the three-dimensional analyses here.

#### 4. DISCUSSION AND CONCLUSIONS

- (i) The circumferential and radial stresses at both 2% and 4% interference in the 3-D analysis show marked variations in the thickness direction (Fig. 3). Although there is little variation between the values at the mid-plane and the 3/4 thickness plane, the values at the surface of the plate, especially close to the hole, are significantly different. In particular, at the hole, with 4% interference the radial stress at the surface is approximately half that at the mid-plane. A reduction in the radial stress (or contact pressure) at the surface is to be expected, because the greater freedom to yield at the surface permits the specified displacement to be achieved at lower pressure. The occurrence of tensile circumferential stresses at the surface (again near the hole) follows from the lower contact pressure.
- (ii) The stresses in the interior of the plate (ie. at the mid- and 3/4-thickness planes) in the 3-D analysis of Fig. 3 show good agreement with the values obtained in the 2-D plane strain analysis of Fig. 4(b).
- (iii) The residual circumferential and radial stresses after load removal, as given by the 3-D analysis, are shown in Fig. 5. Again there is little difference between the stresses in the interior of the plate, but the stresses at the surface are noticeably different; the difference between

the stresses at the surface and in the interior is, however, less than in Fig. 3.

- (iv) The residual stresses in the interior of the plate in the 3-D analysis of Fig. 5 are in good agreement with the plane strain residual stresses of Fig. 6(b).
- (v) In the 3-D analysis, near the hole, neither the radial nor the circumferential stresses at the surface change significantly between 2% and 4% interference (Fig. 3). However, the "waviness" of the surface stress plots (which is even more marked for the residual stresses of Fig. 5) suggests that perhaps the finite element mesh size near the surface was not sufficiently fine, especially in the thickness direction. (See also (vii) below.)
- (vi) The through-thickness stresses (ie. the direct stresses in the thickness direction) are shown in Fig. 7. Naturally, these stresses are zero on the plate surface. Under interference loading, the values at the mid-plane are in good agreement with the plane strain values of Fig. 8(a). The corresponding residual stresses, shown in Fig. 9, exhibit some differences from the plane strain values of Fig. 8(b); in particular, near the hole after 2% cold working the stresses from the 3-D analysis are somewhat less than the plane strain values, whilst after 4% cold working the 3-D stresses do not exhibit the reverse yielding apparent in Fig. 8(b).
- (vii) In Fig. 10 the circumferential, radial, and through-thickness stresses at the bore for interference loading are shown as a function of the thickness co-ordinate. It can be seen that all stresses exhibit the most rapid variation over the element adjacent to the surface (the thickness of which is 1/16 of the plate thickness.) It is possible that use of a finer mesh would have modified both the depth over which this change occurred and also the surface stress values. The analogous results for the residual stresses are shown in Fig. 11 and the same trends are evident.
- (viii) Because the finite element mesh size in the radial direction is relatively coarse in the 3-D analysis, the calculated locations of the elastic-plastic boundaries may not be accurate. As already remarked, in the 2-D analysis a mesh size half that of the 3-D analysis was used. Computational considerations dictated the need for a coarser mesh in the 3-D analysis.
- (ix) Turning now to strains, it can be seen from Fig. 12 that the circumferential and radial strains at both 2% and 4% interference in the 3-D analysis show much less variation in the thickness direction than do the associated stresses; in fact, the circumferential strains show hardly any variation at all. (See also (xiii) below.) This effect may be due in some measure to the specified displacement applied at the interface. The strains of Fig. 12 are consistent with the plane strain values of Fig. 13(b).

- (x) Similar remarks apply to the residual circumferential and radial strains, those for the 3-D analysis being shown in Fig. 14, and for the plane strain analysis in Fig. 15(b).
- (xi) The through-thickness strains (ie. the direct strains in the thickness direction from the 3-D analysis are shown in Fig. 16 for interference loading. The very low values found in the interior of the plate would have been expected, being consistent with plane strain behaviour. However, the strains at the surface are very much less than the 2-D plane stress values of Fig. 17(a).
- (xii) Similar remarks apply to the residual through-thickness strains, those for the 3-D analysis being shown in Fig. 18, and for the 2-D plane stress analysis in Fig. 17(b).
- (xiii) In Fig. 19 the circumferential, radial and through-thickness strains (for interference loading) at the bore are shown as functions of the thickness co-ordinate. As already observed in (ix) above, the circumferential strain shows virtually no variation, although some changes in the other strains are apparent near the surface. Similar remarks apply to the residual strains shown in Fig. 20.
- (xiv) Load versus strain energy density plots (Figs. 21 and 22) show a reverse slope effect during the unloading phase. The possible significance of this effect in relation to fatigue life enhancement has been discussed in Ref. 3. This effect disappears at a non-dimensional radius of about 1.5, although that location should be regarded as approximate.
- (xv) The strain energy density distribution at the bore is shown as a function of the thickness co-ordinate in Fig. 23. Markedly lower values are apparent near the plate surface. This is to be expected in view of the lower radial pressure near the surface, coupled with fairly constant displacements.

## 5. REFERENCES

1. Carey, R.P. and Hoskin, B.C. A Finite Element Procedure for Interference-Fit and Cold-Working Problems with Limited Yielding. Dept. Defence, Aeronautical Research Laboratories, Structures Report 425, Dec. 1986.
2. Carey, R.P. Computed Stress and Strain Distributions under Interference-Fit and after Cold-Working. Dept. Defence, Aeronautical Research Laboratories, Structures Technical Memorandum 466, August 1987.
3. Jones, R., Wong, A.K., Heller, M. and Williams, J.F. The Role of Energy Related Parameters in Life Enhancement Procedures. Proceedings of the 5th International Conference in Australia on Finite Element Methods, August 18-21, 1987, pp 244-246.

**Table 1. Assumed Material Properties**

Property	Plate	Pin
Modules of Elasticity (MPa)	69000	209000
Poisson's Ratio	0.33	0.30
Yield Point (MPa)	480	1720
Strain Hardening Slope (MPa)	1.200	486

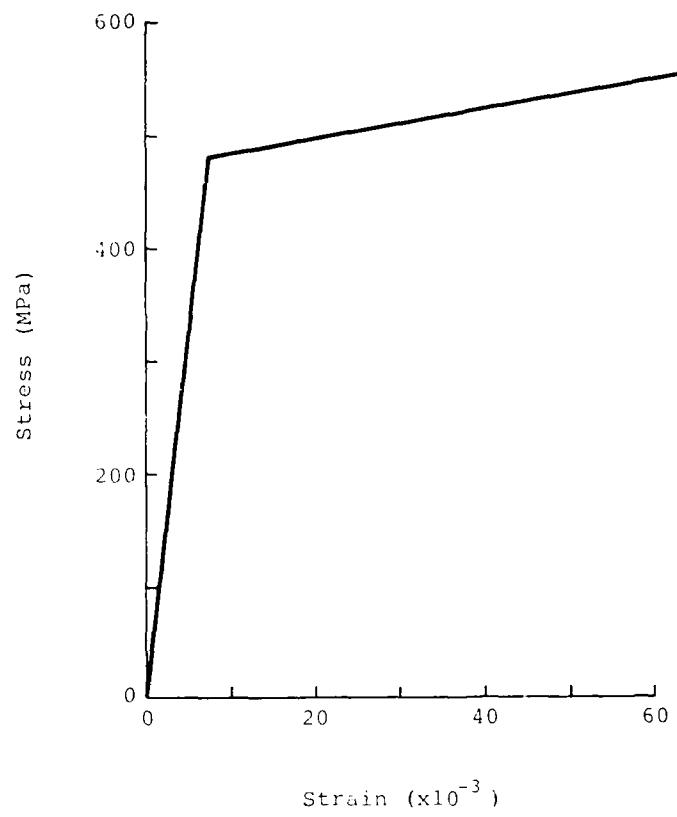


FIG. 1. ASSUMED STRESS-STRAIN BEHAVIOUR FOR PLATE MATERIAL

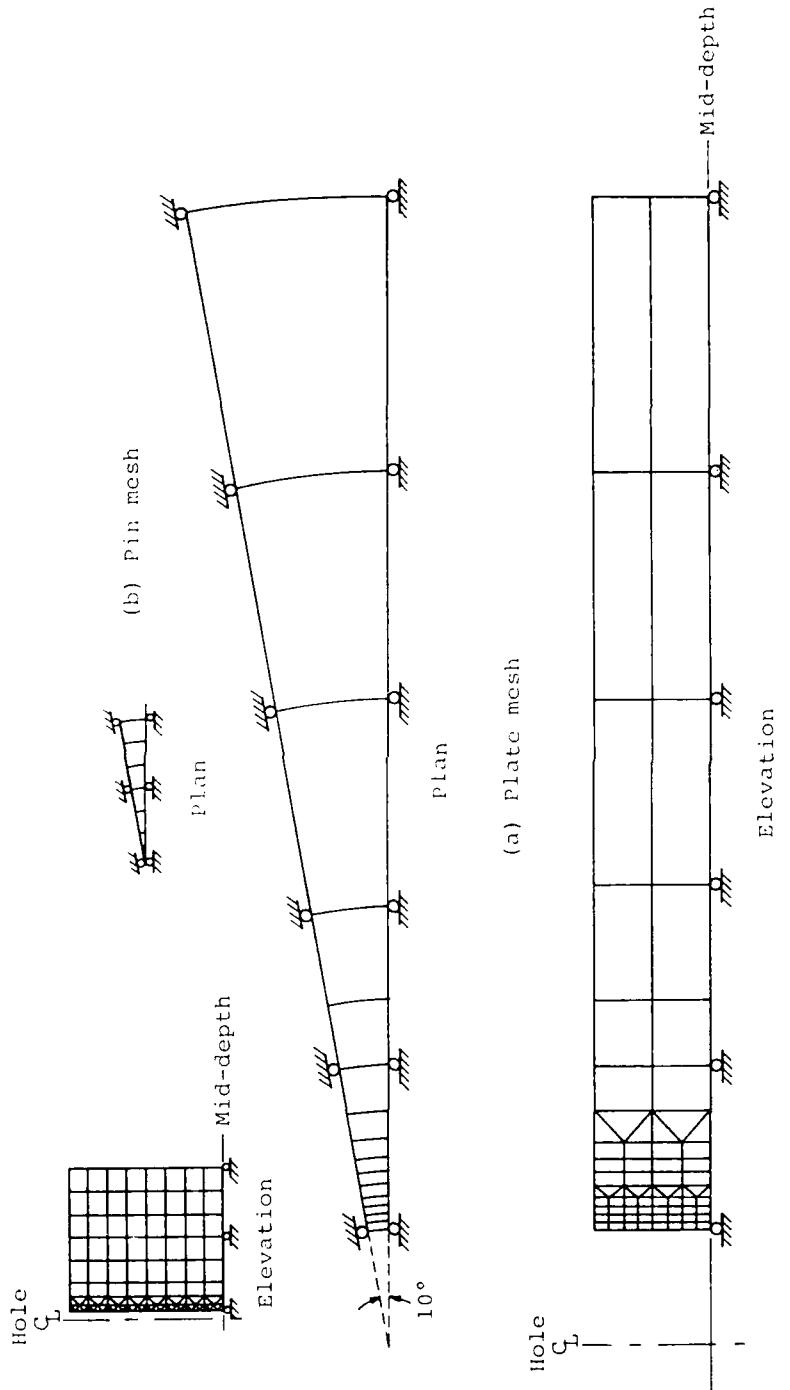


FIG. 2. FINITE ELEMENT MESHES FOR PIN AND PLATE

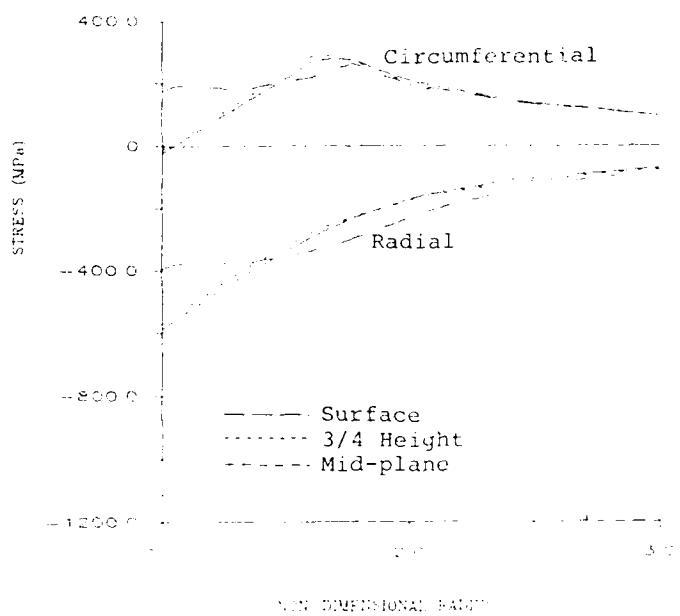


FIG. 3 (a) 2% INTERFERENCE

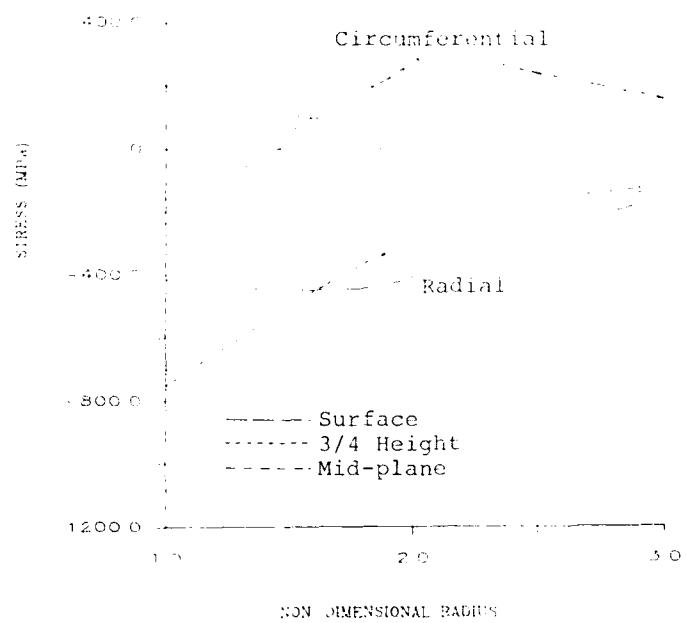


FIG. 3 (b) 4% INTERFERENCE

FIG. 3. CIRCUMFERENTIAL AND RADIAL STRESSES IN 3-D ANALYSIS AT (a) 2% INTERFERENCE AND (b) 4% INTERFERENCE. (MESH NODE POSITIONS INCLUDING MID-SIDE NODES ARE SHOWN ON FIG. 3(a))

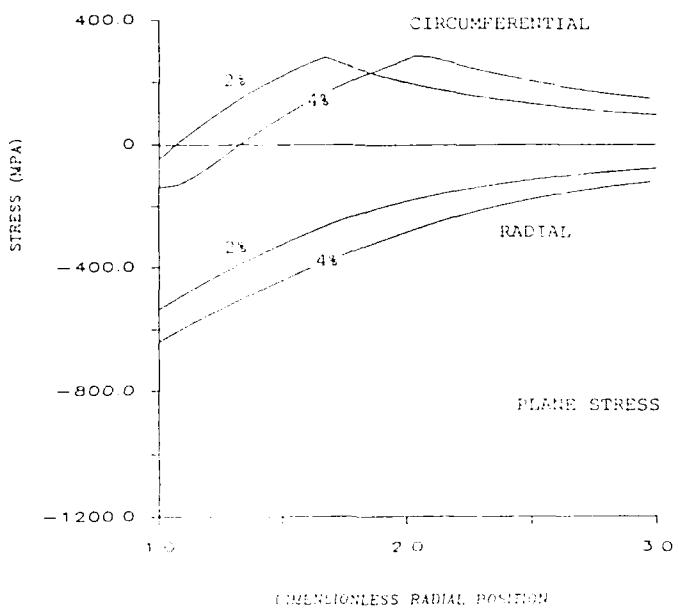


FIG. 4 (a)

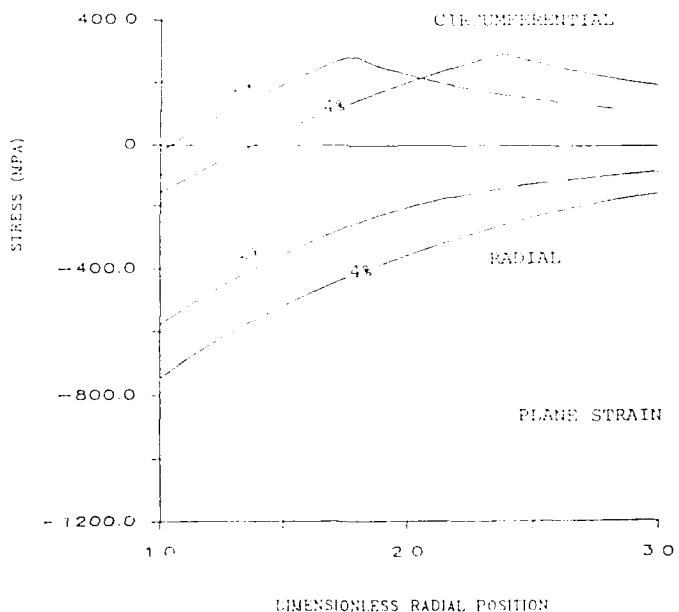


FIG. 4 (b)

FIG. 4. CIRCUMFERENTIAL AND RADIAL STRESSES IN 2-D ANALYSIS AT 2% AND 4% INTERFERENCE ASSUMING (a) PLANE STRESS AND (b) PLANE STRAIN CONDITIONS.

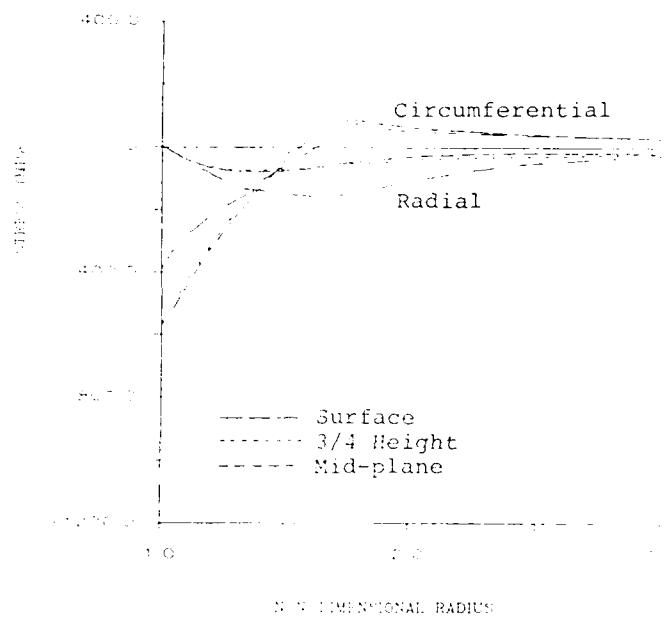


FIG. 5 (a) AFTER 2% COLD-WORKING

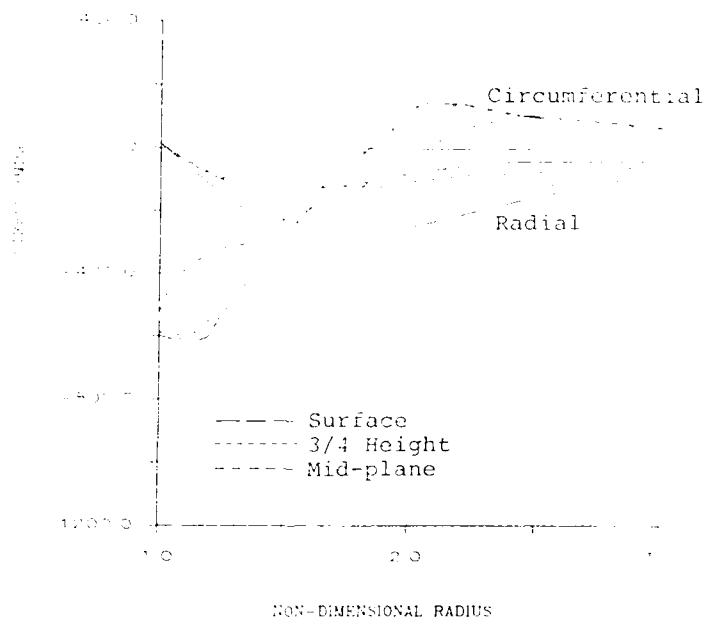


FIG. 5 (b) AFTER 4% COLD-WORKING

FIG. 5. RESIDUAL CIRCUMFERENTIAL AND RADIAL STRESSES IN 3-D ANALYSIS AFTER (a) 2% COLD-WORKING AND (b) 4% COLD-WORKING.

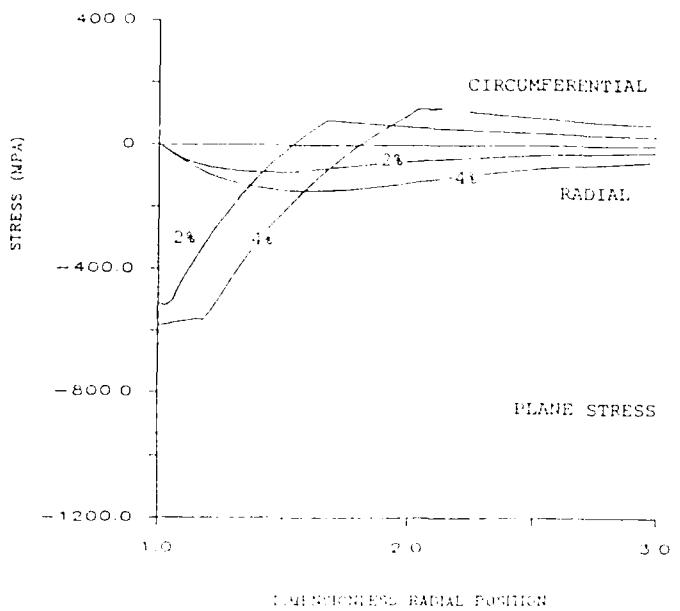


FIG. 6 (a)

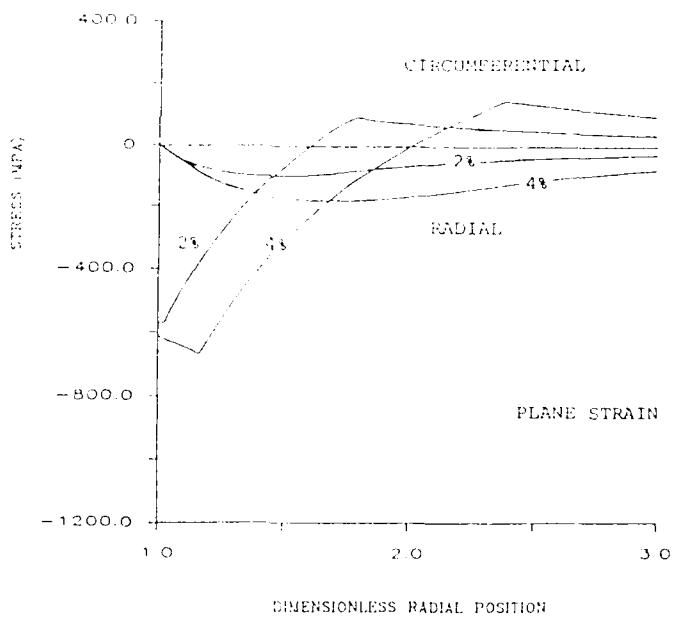


FIG. 6 (b)

FIG. 6. RESIDUAL CIRCUMFERENTIAL AND RADIAL STRESSES IN 2-D ANALYSIS AFTER 2% AND 4% COLD-WORKING ASSUMING  
 (a) PLANE STRESS AND (b) PLANE STRAIN CONDITIONS.

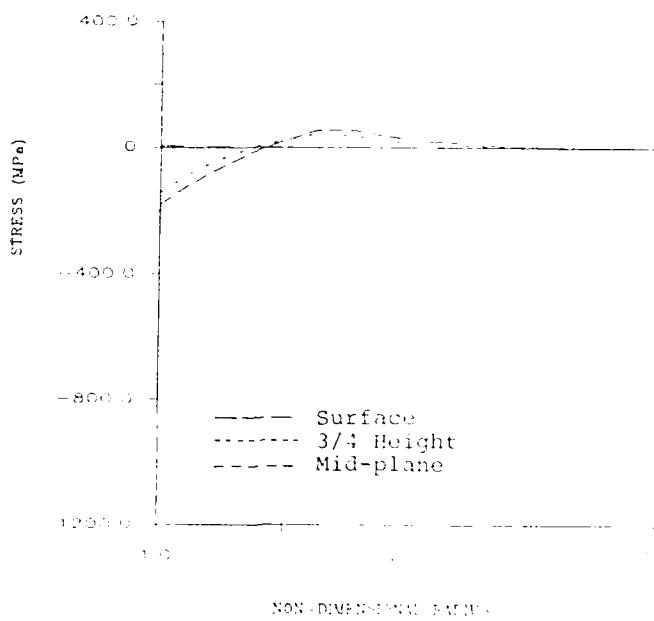


FIG. 7 (a) 2% INTERFERENCE

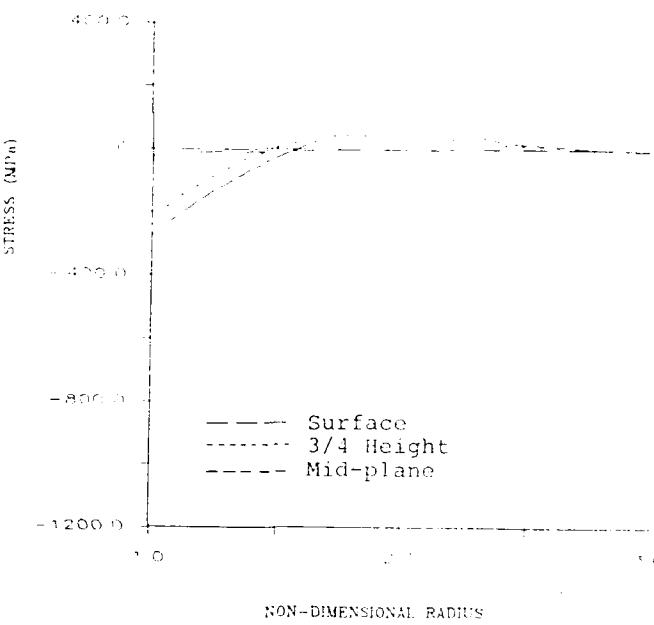


FIG. 7 (b) 4% INTERFERENCE

FIG. 7. THROUGH-THICKNESS STRESSES IN 3-D ANALYSIS AT  
(a) 2% INTERFERENCE AND (b) 4% INTERFERENCE

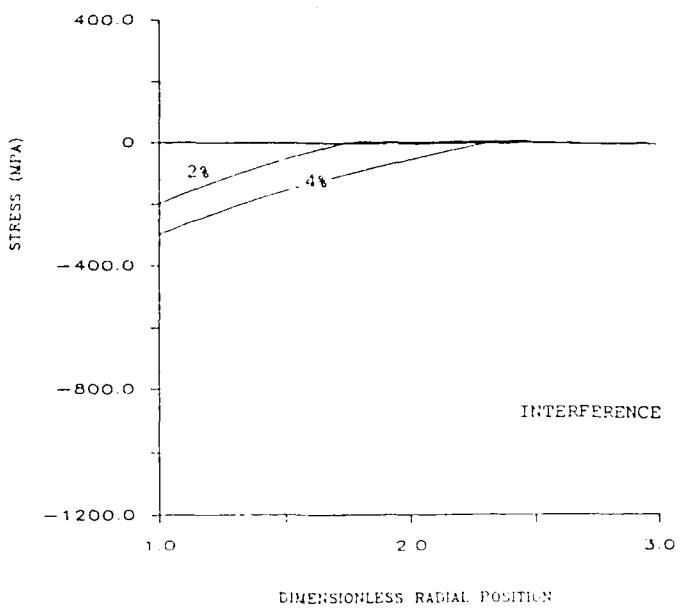


FIG. 8 (a)

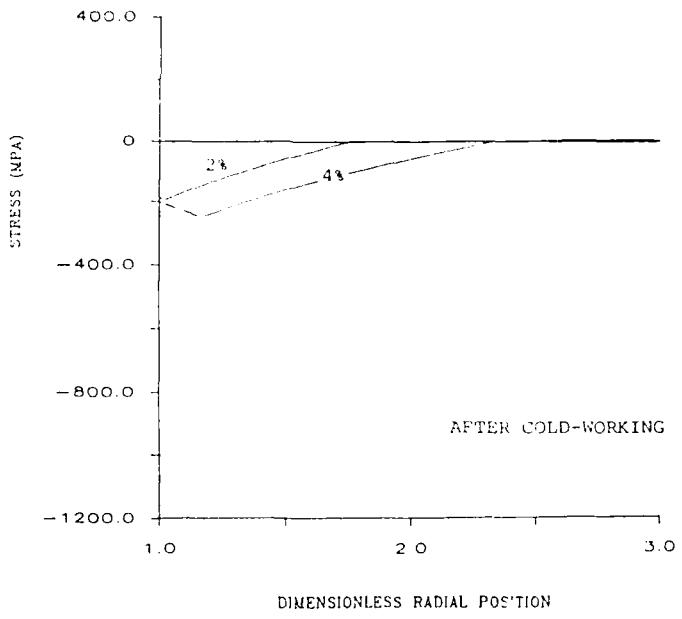


FIG. 8 (b)

FIG. 8. THROUGH-THICKNESS STRESS IN 2-D PLANE STRAIN ANALYSIS  
 (a) AT 2% AND 4% INTERFERENCE AND (b) AFTER UNLOADING

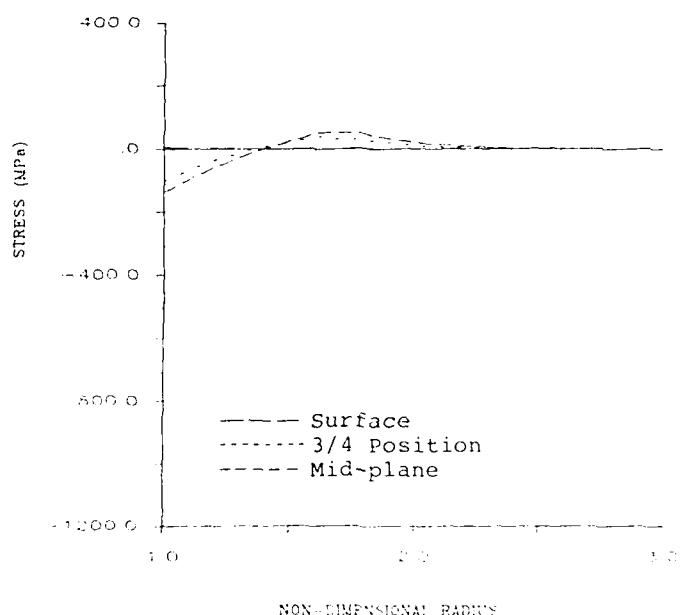


FIG. 9 (a) AFTER 2% COLD-WORKING

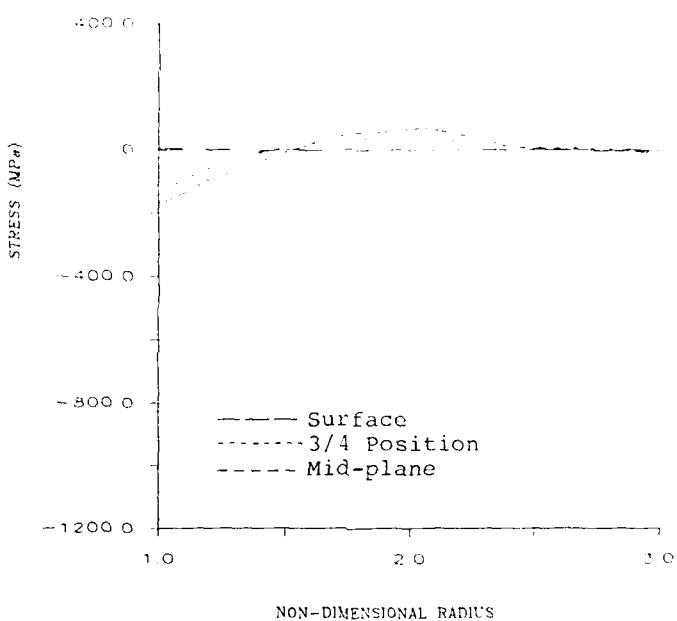


FIG. 9 (b) AFTER 4% COLD-WORKING

FIG. 9. RESIDUAL THROUGH-THICKNESS STRESSES IN 3-D ANALYSIS  
AFTER (a) 2% COLD-WORKING AND (b) 4% COLD-WORKING

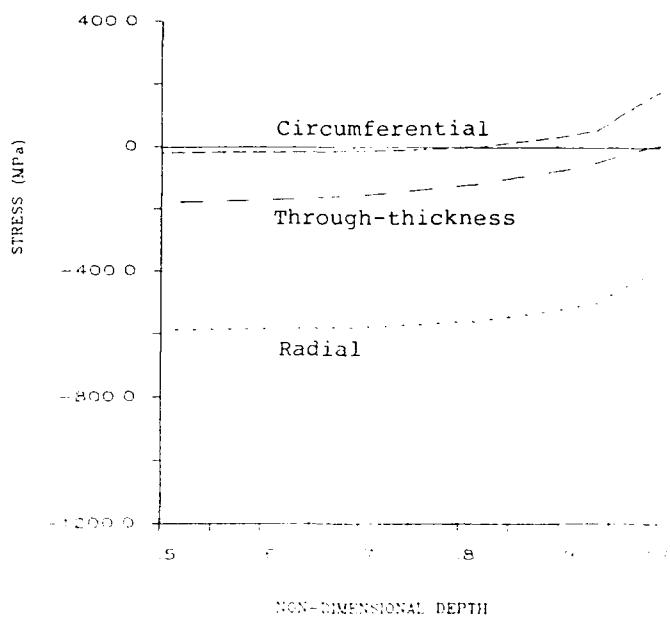


FIG. 10 (a) 2% INTERFERENCE

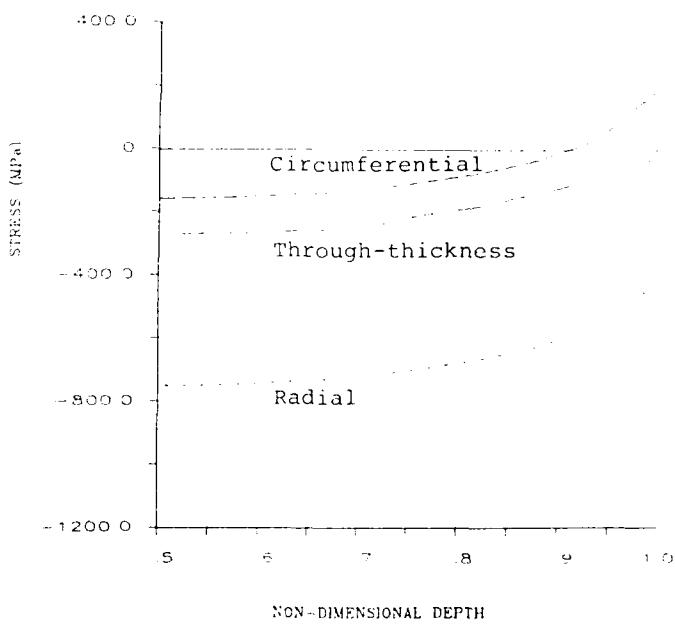


FIG. 10 (b) 4% INTERFERENCE

FIG. 10. STRESSES ALONG BORE AT (a) 2% INTERFERENCE AND  
(b) 4% INTERFERENCE

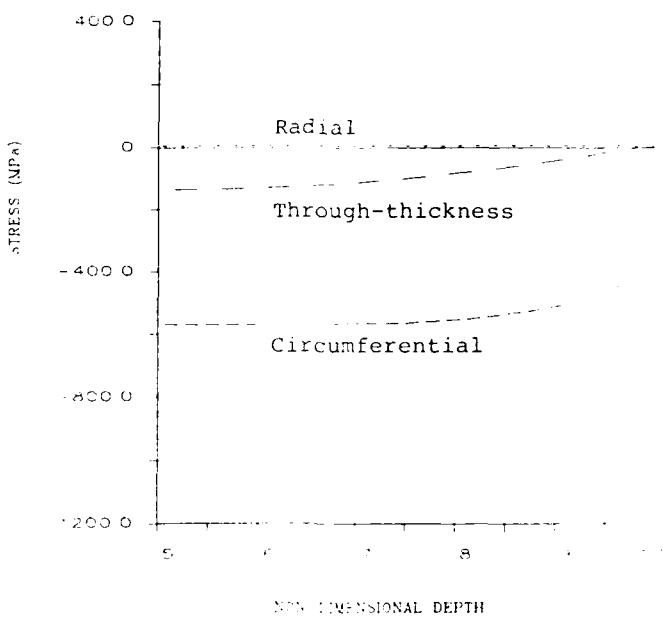


FIG. 11 (a) AFTER 2% COLD-WORKING

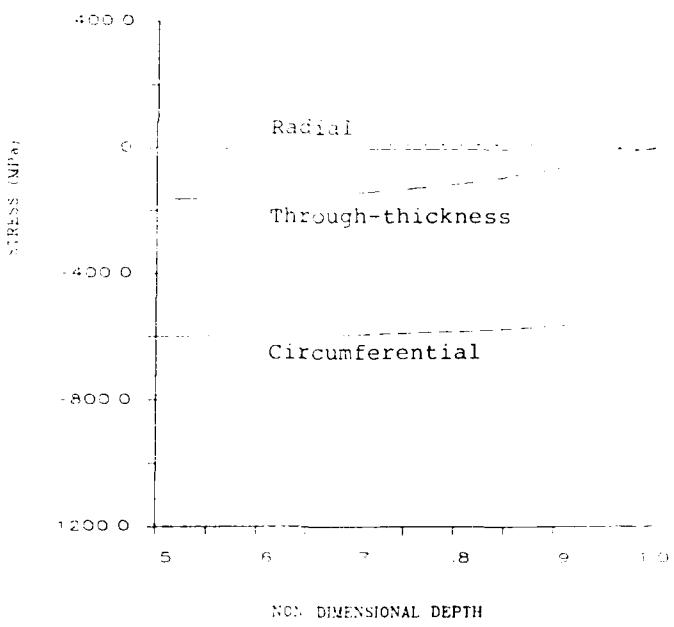


FIG. 11 (b) AFTER 4% COLD-WORKING

FIG. 11. RESIDUAL STRESSES ALONG THE BORE AFTER  
 (a) 2% COLD-WORKING AND (b) 4% COLD-WORKING

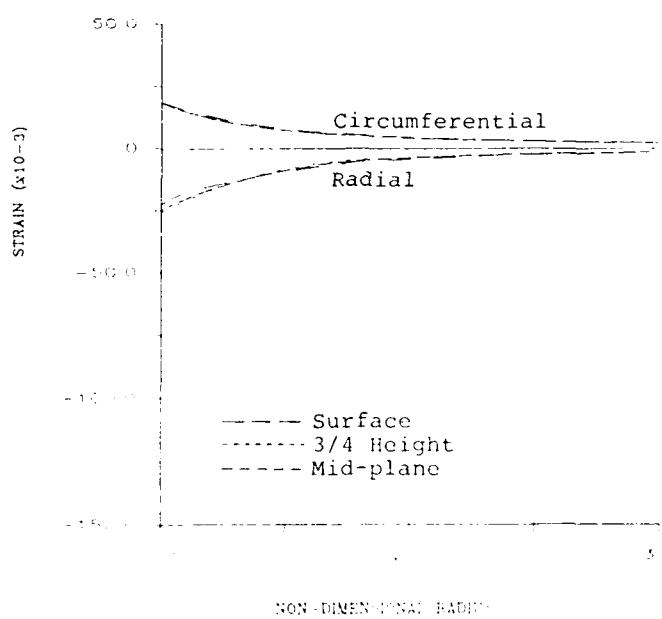


FIG. 12 (a) 2% INTERFERENCE

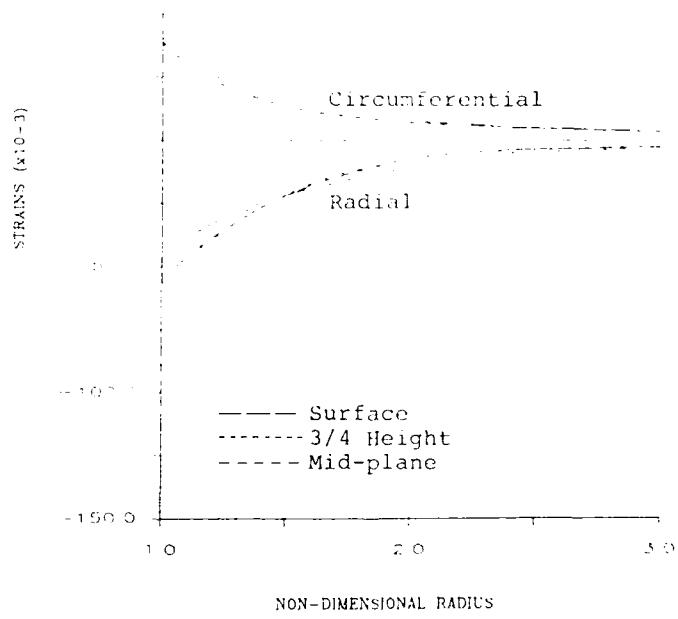


FIG. 12 (b) 4% INTERFERENCE

FIG. 12. CIRCUMFERENTIAL AND RADIAL STRAINS IN 3-D ANALYSIS  
AT (a) 2% INTERFERENCE AND (b) 4% INTERFERENCE

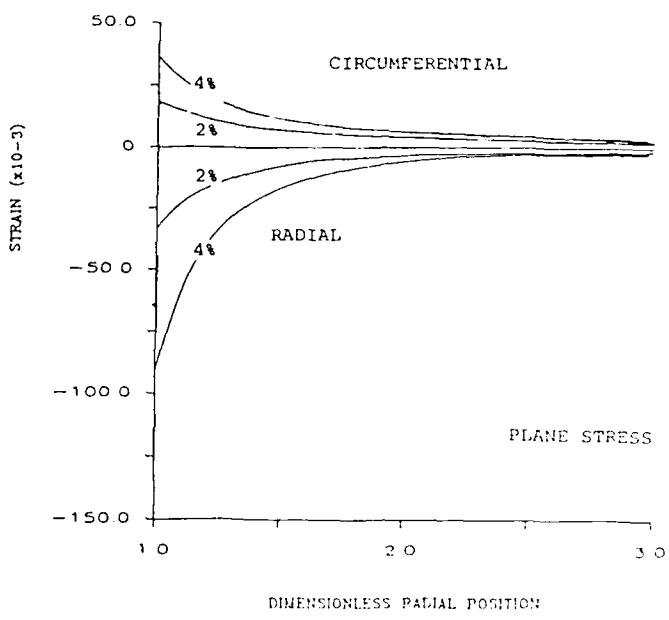


FIG. 13 (a)

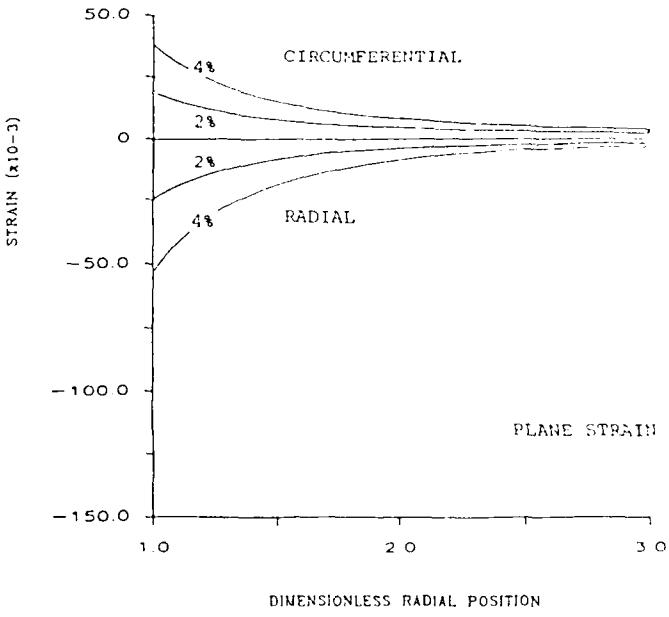


FIG. 13 (b)

FIG. 13. CIRCUMFERENTIAL AND RADIAL STRAINS IN 2-D ANALYSIS AT 2% AND 4% INTERFERENCE ASSUMING (a) PLANE STRESS AND (b) PLANE STRAIN CONDITIONS

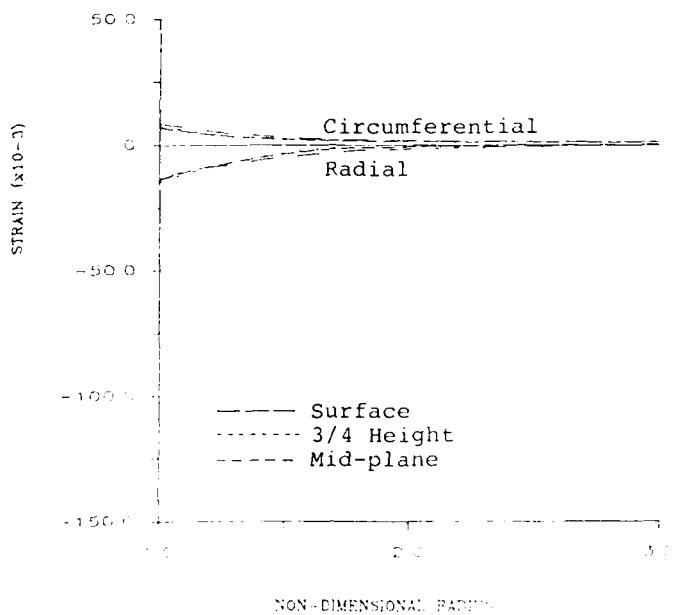


FIG. 14 (a) AFTER 2% COLD-WORKING

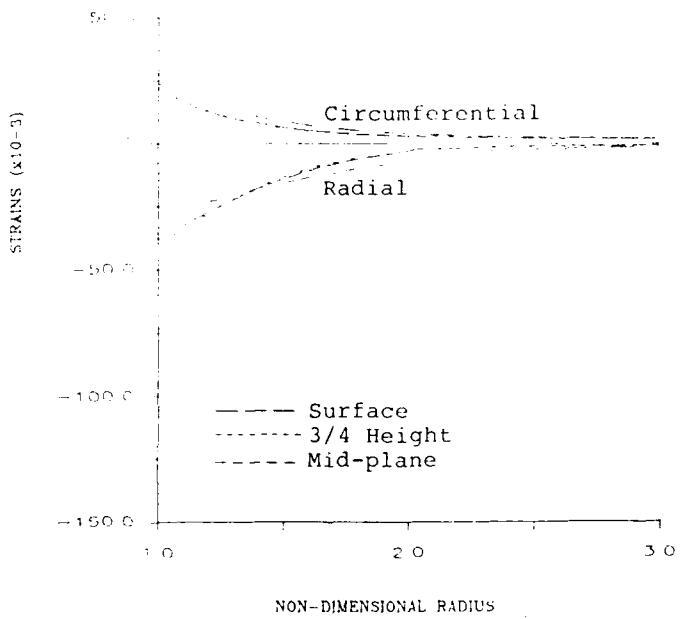


FIG. 14 (b) AFTER 4% COLD-WORKING

FIG. 14. RESIDUAL CIRCUMFERENTIAL AND RADIAL STRAINS IN 3-D ANALYSIS AFTER (a) 2% COLD-WORKING AND (b) 4% COLD-WORKING

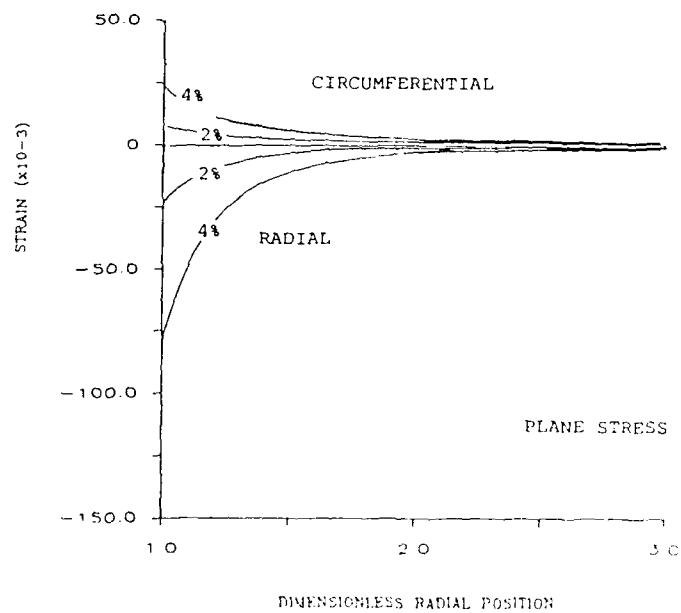


FIG. 15 (a)

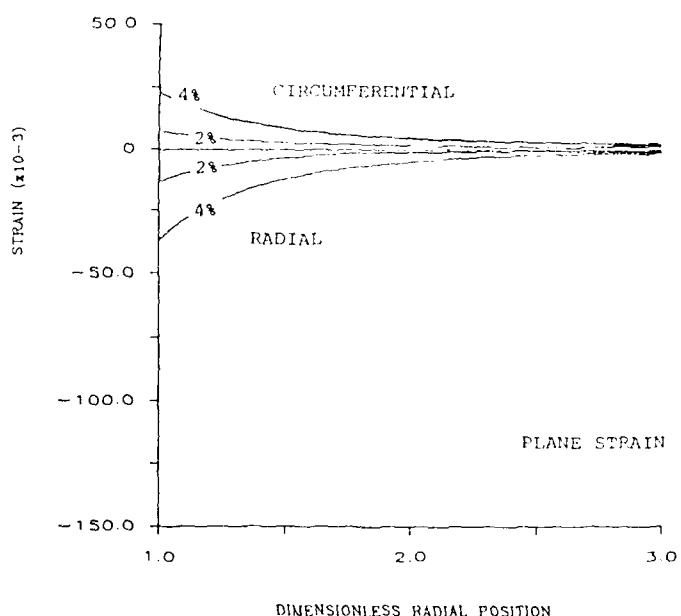


FIG. 15 (b)

FIG. 15. RESIDUAL CIRCUMFERENTIAL AND RADIAL STRAINS IN 2-D ANALYSIS AFTER 2% AND 4% COLD-WORKING ASSUMING  
 (a) PLANE STRESS AND (b) PLANE STRAIN CONDITIONS

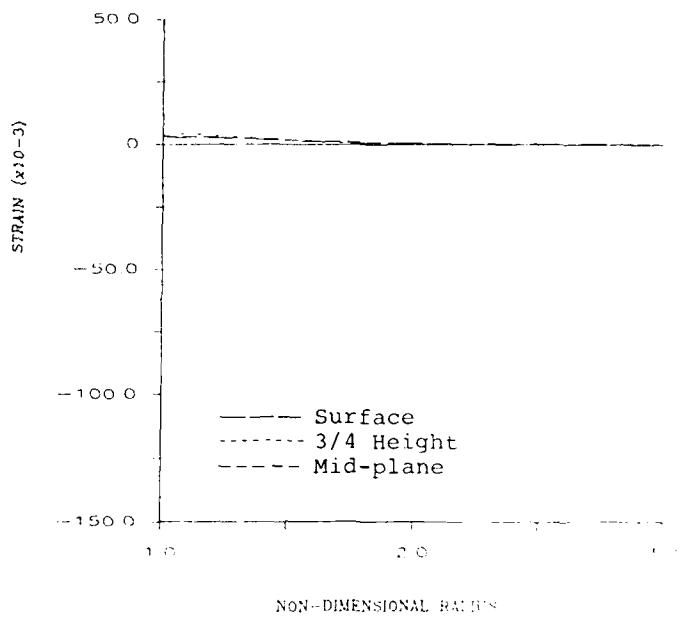


FIG. 16 (a) 2% INTERFERENCE

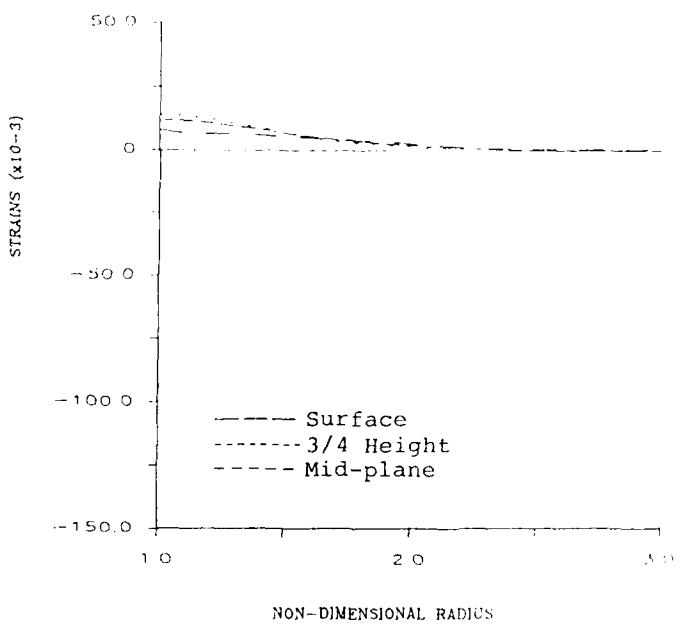


FIG. 16 (b) 4% INTERFERENCE

FIG. 16. THROUGH-THICKNESS STRAINS IN 3-D ANALYSIS AT  
(a) 2% INTERFERENCE AND (b) 4% INTERFERENCE

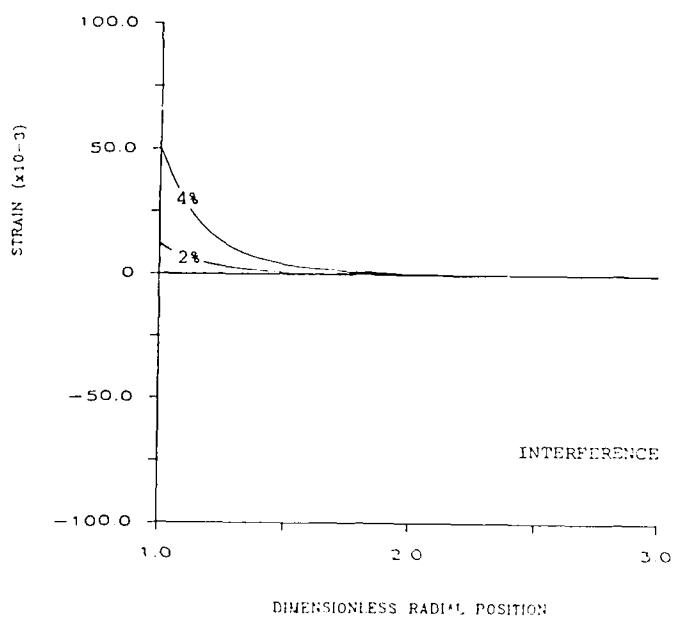


FIG. 17 (a)

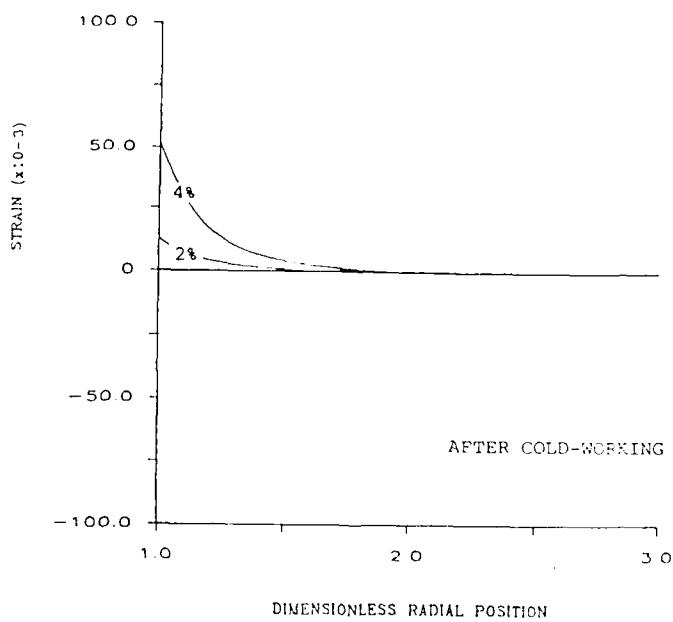


FIG. 17 (b)

FIG. 17. THROUGH-THICKNESS STRAINS IN 2-D PLANE STRESS ANALYSIS  
 (a) AT 2% AND 4% INTERFERENCE AND (b) AFTER UNLOADING

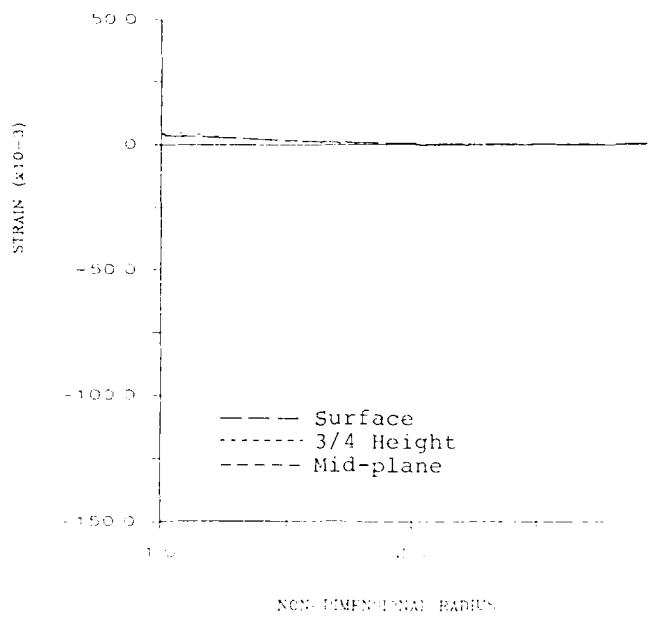


FIG. 18 (a) AFTER 2% COLD-WORKING

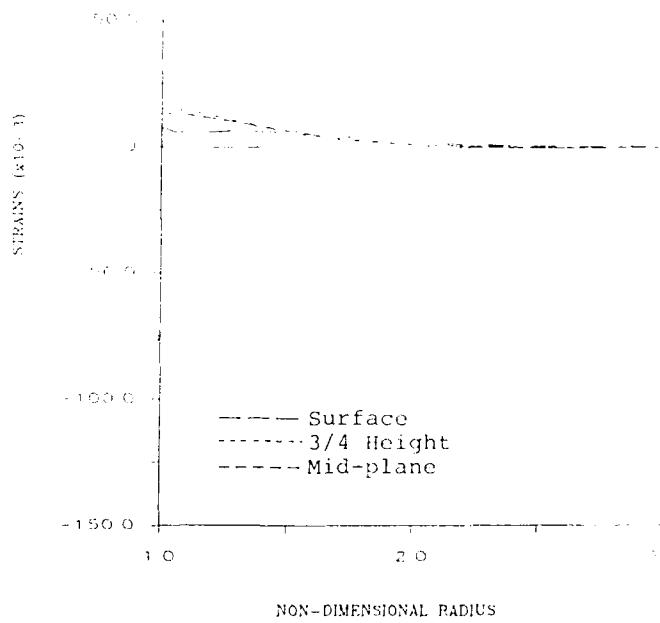


FIG. 18 (b) AFTER 4% COLD-WORKING

FIG. 18. RESIDUAL THROUGH-THICKNESS STRAINS IN 3-D ANALYSIS  
AFTER (a) 2% COLD-WORKING AND (b) 4% COLD-WORKING

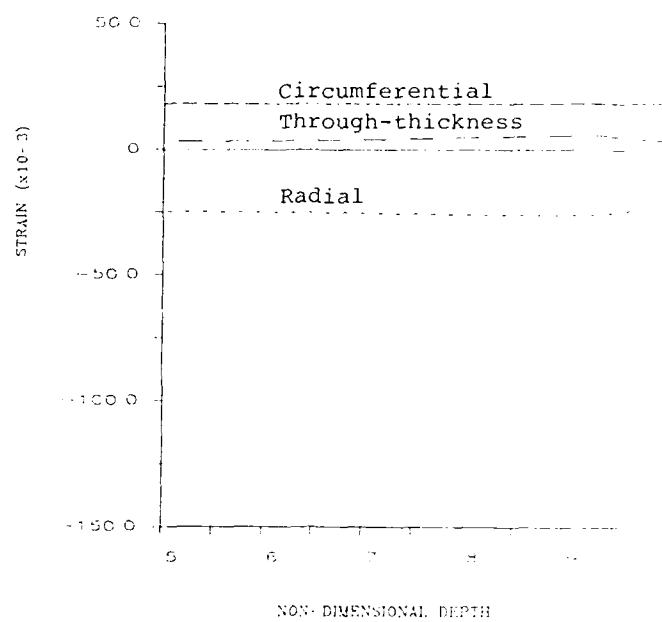


FIG. 19 (a) 2% INTERFERENCE

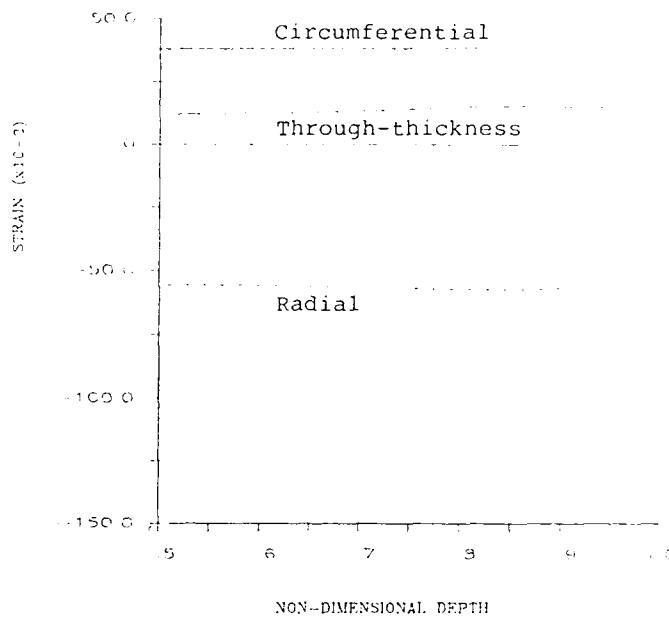


FIG. 19 (b) 4% INTERFERENCE

FIG. 19. STRAINS ALONG THE BORE AT (a) 2% INTERFERENCE AND (b) 4% INTERFERENCE

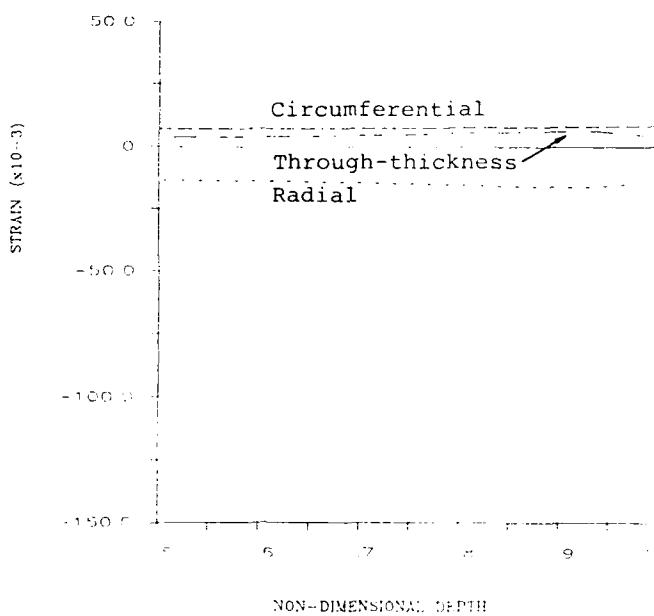


FIG. 20 (a) AFTER 2% COLD-WORKING

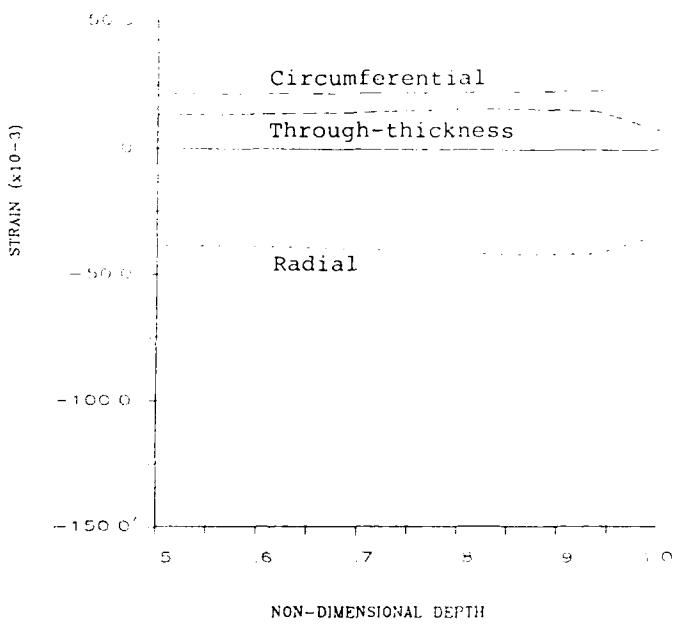


FIG. 20 (b) AFTER 4% COLD-WORKING

FIG. 20. RESIDUAL STRAINS ALONG THE BORE AFTER  
(a) 2% COLD-WORKING AND (b) 4% COLD-WORKING

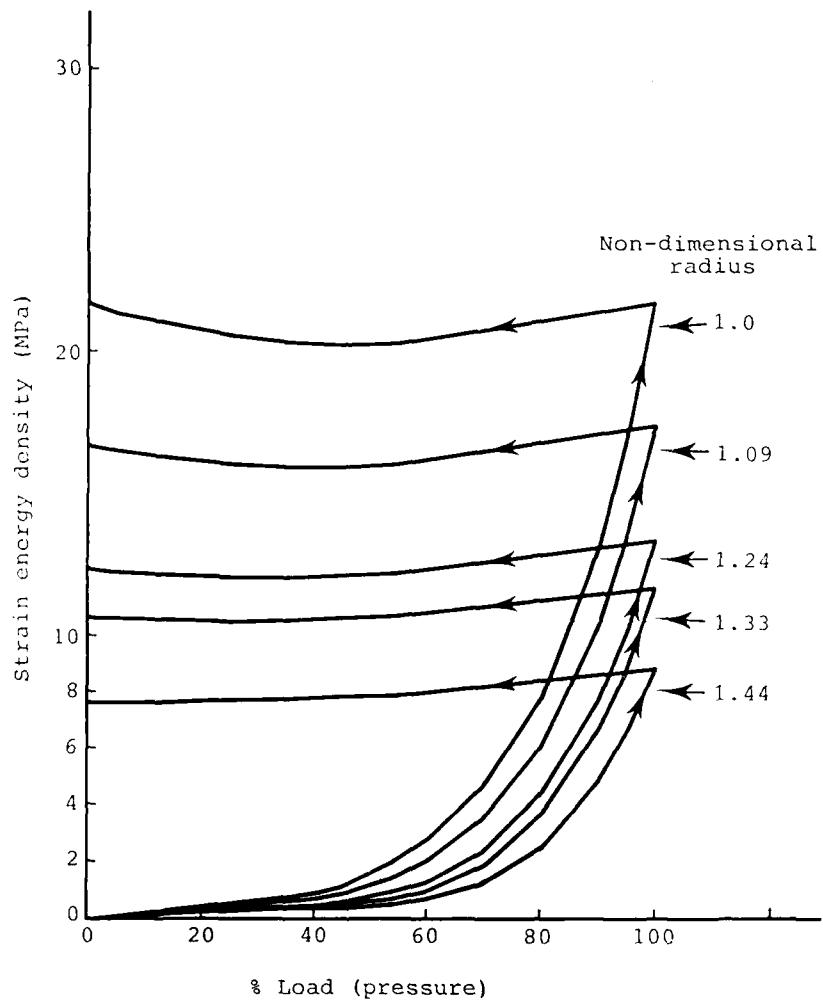


FIG. 21. STRAIN ENERGY RESPONSE AT VARIOUS DISTANCES FROM THE BORE AT THE PLATE SURFACE. LOADING TO 4% FOLLOWED BY UNLOADING.

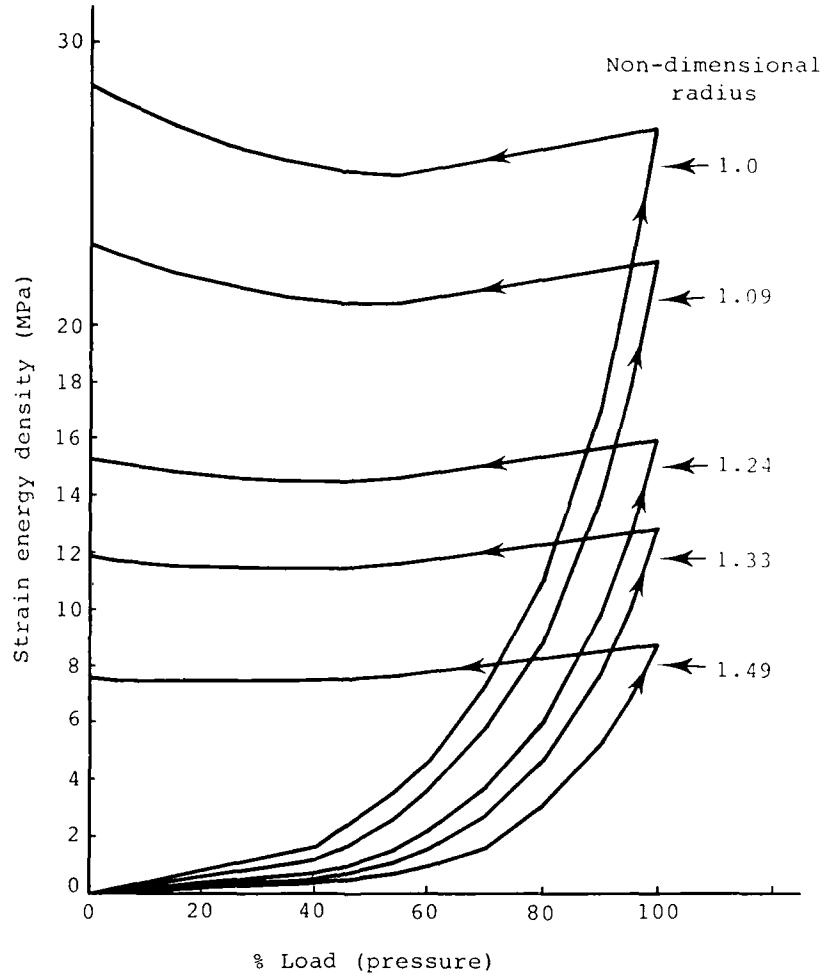


FIG. 22. STRAIN ENERGY RESPONSE AT VARIOUS DISTANCES FROM THE BORE ON A PLANE AT 0.563 OF THE PLATE THICKNESS FROM THE SURFACE (APPROX MID-PLANE POSITION). LOADING TO 4% FOLLOWED BY UNLOADING.

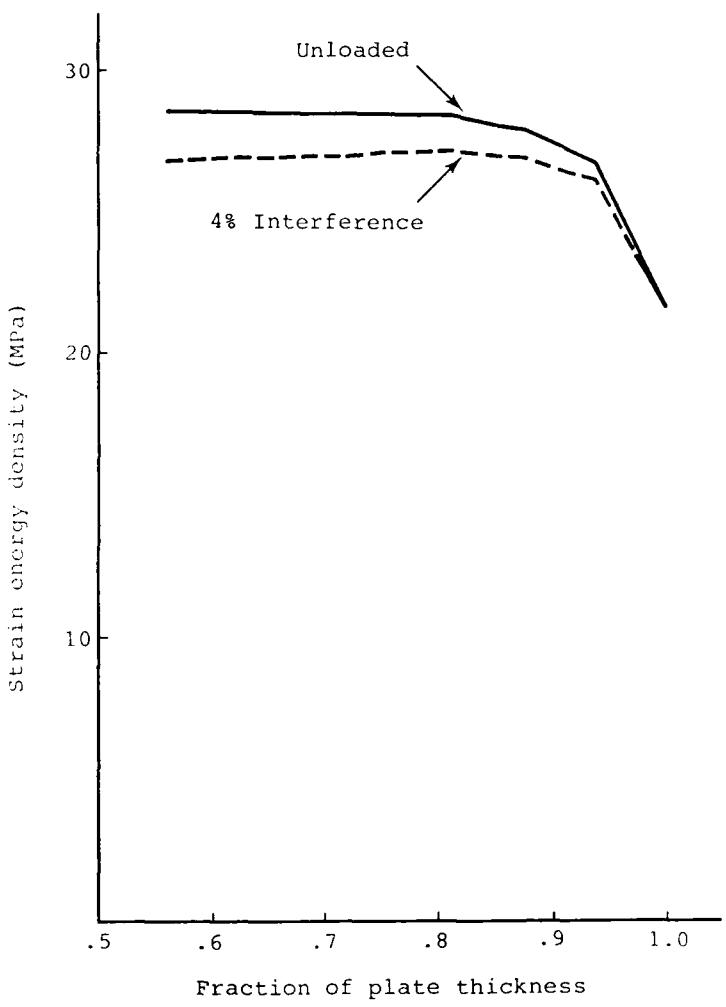


FIG. 23. STRAIN ENERGY DISTRIBUTION ALONG THE BORE AT 4% INTERFERENCE AND AFTER UNLOADING (COLD-WORKED CONDITION)

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